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COMMITTEE ON THE PEACEFUL USES OF
OUTER SPACE
Scientific and Technical Sub-Committee
Working Group on the Use of Nuclear
Power Sources in Outer Space

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Note by the Secretariat

1. The Secretary-General, in a note dated 30 June 1989, drew the attention of the Governments of the States Members of the United Nations to paragraph 12 of the report of the Working Group on the Use of Nuclear Power Sources in Outer Space on the work of its seventh session, in 1989 (A/AC.105/429, annex III), as adopted by the Scientific and Technical Sub-Committee of the Committee on the Peaceful Uses of Outer Space, which reads as follows:

> "... The Working Group considered it essential to continue the study of the problem of collisions with space debris. The Working Group called for the preparation of national research on this question and proposed that delegations submit the results to the Scientific and Technical Sub-Committee."

2. The Secretary-General also drew the attention of the Governments to paragraph 61 of the report of the Scientific and Technical Sub-Committee on the work of its twenty-sixth session, in 1989 (A/AC.105/429), in which "the Sub-Committee called upon Member States to submit their working papers for the Working Group well in advance of its next session, to be held in 1990".

3. Furthermore, the Secretary-General directed the attention of the Governments to paragraph 34 of the report of the Committee on the Peaceful Uses of Outer Space on the work of its thirty-second session, in June 1989, which reads:

> "The Committee considered it essential that more attention be paid by Member States to the problem of collisions with space debris and other aspects of space debris. The Committee called for the continuation of national research on this question."

4. The Secretary-General requested that any information that the Governments might wish to submit should reach the Secretariat by 15 December 1989. The present document contains information received up to 13 January 1990 in response to the above-mentioned note. Further information will be circulated as addenda to the present document.

AUSTRIA

[Original: English]

Prof. Siegfried Bauer, head of the Institute for Meteorology and Geophysics of the University of Graz, has been actively involved in preparing study reports on space debris, as follows:

(a) "Environmental effects of space activities": report submitted by the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU) and the International Astronautical Federation (IAF) to the Scientific and Technical Sub-Committee of the Committee on the Peaceful Uses of Outer Space of the United Nations; prepared by L. Perek, on behalf of IAF, and S. Bauer, on behalf of COSPAR (A/AC.105/420);

(b) "Space debris": report of the ESA Space Debris Working Group, ESA-SP 1109. Prof. Bauer has been a member of this Working Group.

Furthermore, Prof. Bauer is Chairman of the COSPAR Panel on Potentially Environmentally Detrimental Activities in Space, in which the problem of collisions with space debris is being discussed.

CZECHOSLOVAKIA

[Original: English]

Czechoslovakia's activities in the peaceful exploration and uses of outer space are aimed to accomplish scientific and national economic tasks.

As regards national research in the field of space debris, this constitutes a minor part of the overall astronomical research. A study has recently been written by two authors: L. Perek, on behalf of Czechoslovakia and the International Astronautical Federation (IAF), and S. J. Bauer, on behalf of the Committee on Space Research (COSPAR), on the results of research in this field. The study was published in 1988 as document A/AC.105/420.

Apart from this, Czechoslovakia regularly co-operates with the International Academy of Astronautics (IAA), namely, with its Committee on Space Safety and Rescue, in organizing annual congresses.

FINLAND

[Original: English]

The prevention of the continued accumulation of space debris as well as research on the problem of space debris as a whole have become important as manned space flights have increased. According to established national guidelines, Finland does not engage in any research and development activities relating to manned space flights. Consequently, no national research on the problem of space debris is currently under way in Finland. Finland does, however, closely monitor international research efforts in this field in the context of its participation in European Space Agency (ESA) programmes.

PAKISTAN

[Original: English]

Accidental failures of propulsion systems constitute the greatest contribution to fragmentation debris pollution. While launch vehicle failures early in flight are often widely publicized, upper-stage failures in orbit, which are not uncommon, rarely receive attention. By far, the single largest source and the cause for the greatest concern is the growing amount of space debris produced during satellite fragmentation. Newly launched spacecraft face increasing risk from fragments which may hit them, causing explosions and more fragmentations. Nevertheless, collisions in space may rightly be feared even more than the explosions. Collisions between rocket bodies and their payloads at velocities of only tens of metres per second produce very minor debris, but at much higher velocities of many kilometres per second ("hyper-velocity") these collisions may generate a very large amount of debris, and detailed studies have shown that far greater amounts of debris are generated in collisions than in explosions. Most of the debris produced in such collisions is too small to be observed from Earth with standard tracking techniques. With the known satellite population in space, growing at the rate of more than 300 objects per year, the probability of two objects colliding in Earth orbit is still very low and to date no satellite fragmentations are known to have been the result of an accidental hyper-velocity collision between two satellites. However, the causes of almost half of all satellite fragmentations are still unknown.

From the studies carried out internationally so far, it may be concluded that the highest collision probabilities occur at altitudes of 800-1,000 km. With the emphasis on high-altitude satellites (800-1,000 km), the calculated probability of collision in this altitude régime has increased by as much as two orders of magnitude. The dispersion pattern of debris produced in the near-Earth, low-altitude atmosphere shows that dispersion can occur anywhere between ground and 100 km. Small-size particles (smaller than 10 microns) are likely to remain in the atmosphere, where they were formed, slowly precipitating to lower levels, and larger particles (100 microns or more) tend to reach the Earth within hours after their production, thereby contaminating a large area around the ground track of satellites.

Notwithstanding the foregoing, it should be borne in mind that some of the factors included in the procedures by which the present probability figures have been obtained could, under certain circumstances, lead to less favourable figures in future. In particular, it may be possible for much more powerful nuclear power reactor devices to be developed and used in future, thereby aggravating the casualty risk in case of failures. Moreover, in the case of satellites carrying nuclear power sources (NPS), circling the Earth in low orbits, the situation is quite different. It therefore follows that any risk calculation regarding NPS must not be judged on the same level with the risk calculations for other common types of activities. In view of the special character of NPS, their use in outer space may be governed by carefully designed and detailed international regulations.

SWEDEN

[Original: English]

Space technology applications and research can constitute important factors in the peaceful development of the world. For certain regions, space techniques are the most practical solutions to improve, e.g., communications, education, mapping and inventory of natural resources.

Space should be accessible to all countries. Pollution of the space environment and the increasing risks of collisions between space debris and spacecraft reduce the accessibility of space for all countries. Should collisions occur with spacecraft carrying nuclear power sources (NPS), the consequences could be very far-reaching.

Over the last few years, space debris have come to be identified as a serious threat to man's exploration and utilizaiton of outer space. This has been indicated in various studies conducted at both the national and the international level.

The dimensions of the problem of space debris are such that they require the immediate attention and active involvement of the international community. The 1967 Treaty on outer space lays down that the exploration and use of outer space shall be the province of all mankind. The common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes is equally well established. Therefore, all States should identify ways and means of addressing the problem of space debris, also keeping in mind the interest of future generations.

Increased knowledge regarding the space environment is necessary to control the amount of space debris. Compilation of, and access to, data on space debris and the tracking and monitoring of the space debris environment cannot be done effectively without international co-operation.

Sweden has not so far undertaken any national studies on space debris. The efforts in this field are channelled into the international forums in which Sweden participates.

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READEX FICHE

Sweden actively supported a resolution on the issue of space debris which was adopted in June 1989 by the European Space Agency (ESA) and which aims at increasing the knowledge of the problem, reducing the production of space debris and promoting the exchange of information and co-operation with other space operators.

Sweden has also raised this issue in the United Nations on several occasions, both with respect to the seriousness of the problem and with respect to our belief in the role that the United Nations has to play in matters of global interest.

At the 1989 session of the Committee on the Peaceful Uses of Outer Space, Sweden together with Australia, Belgium, Canada, the Federal Republic of Germany, the Netherlands and Nigeria, presented a working paper in which it was proposed that the issue of space debris be put on the agenda of the Scientific and Technical Sub-Committee at its next session.

UNITED ARAB EMIRATES

[Original: English]

The United Arab Emirates, for the present, would not be in a position to undertake a national research project on the problem of collisions with space debris.

The United Arab Emirates, on the receipt of information concerning the possibility of space debris entering the airspace of the United Arab Emirates and the Emirates flight information region (FIR), would take necessary disaster prevention/mitigation actions. For this purpose it is suggested that the Scientific and Technical Sub-Committee develop and implement international procedures for the rapid transmission of information regarding the possible approach of space debris to the concerned nations.

The Sub-Committee may also provide guidelines for mitigating the effects of collisions with different types of space debris.

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Note by the Secretariat

Addendum

JAPAN

Annexed hereto are working papers* written by five specialists who are among those researchers playing a major role in scientific studies on space debris at government research laboratories. The future policy of the Government of Japan in this area will not be restricted by the results presented in the papers. The Government of Japan hopes that the working papers, submitted in accordance with paragraph 12 of the report of the Working Group on the Use of Nuclear Power Sources in Outer Space on the work of its seventh session (A/AC.105/429, annex III), will contribute in some way to the further examination of this question.

* The papers are being circulated only in the language of their submission (English).

Annex I

A MODEL OF DEBRIS FRAGMENTATION EXPLOSION

by

Dr. Seishoro Kibe, Senior Researcher,
Structural Mechanics Division

Dr. Tatsuo Yamanaka, Director, Space Technology Research Group,
National Aerospace Laboratory, Science and Technology Agency,
Japan

As space development and utilization activities advance, problems arising from space debris are becoming increasingly serious. Small-size debris (smaller than several centimetres in diameter) must be given special attention because of the lack of ground experimental data and poor observation capability.

Although some experimental data are available, for example, JANNAF, they are confined to relatively large debris (larger than 0.05 m). Satellites can avoid large debris by using orbital data catalogued by SPACECOM and other sources, but in the case of small debris, satellites, including the Space Station, should be protected by shielding structures. Reliable information on small debris is therefore needed in order to design and optimize such structures. However, as mentioned above, it is very difficult or impossible to obtain such information from ground experiments or radar observations. Thus, it is necessary to resort to some kind of fragmentation modelling and extrapolation from large-size debris data.

The authors have been investigating several kinds of fragmentation models, some of which include the effect of stochastic properties of material strength. Figure 1 shows a simple fragmentation model. The model explains the experimental fact that weight and cross-sectional data of relatively large debris have a log normal distribution, and gives the rationale for the smooth extrapolation of small-size debris distribution from large-size data.

Two basic assumptions underlying this analysis are as follows:

(a) A square plate is fragmented into N x N pieces along the grid lines indicated in figure 1;

(b) Each grid line is randomly located between zero and L, and its location can be determined using a series of uniform random numbers.

For the case of N=15, a Monte Carlo simulation was conducted. The results are shown in figures 2 and 3. Debris percentage is plotted against area and circumferential length on the log normal probabilistic paper. This fragmentation model can explain the log normal distribution of weight and cross-section in relatively large-size debris data. Also, in estimating the unknown distribution of small-size debris, it seems reasonable to extrapolate smoothly from large-size debris data. In addition to the above results, this model suggests that

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circumferential length, a very important index with respect to energy emission, is also log normally distributed.

The authors are also planning to conduct a simulation using another model to investigate fragmentation behaviour in a pressure vessel explosion, which is different from fragmentation induced by explosives.

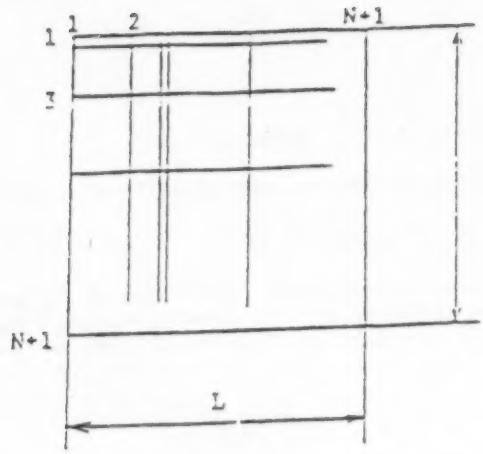

Fig.1

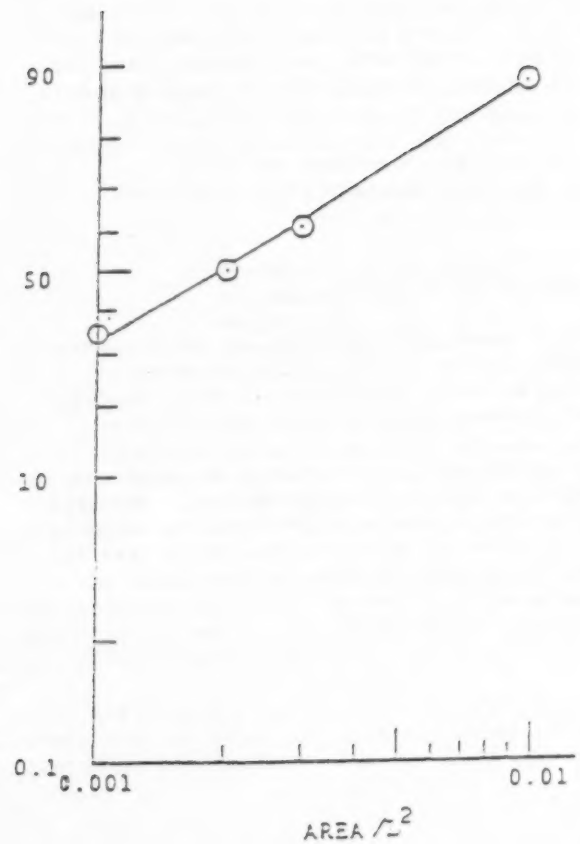

Fig.2

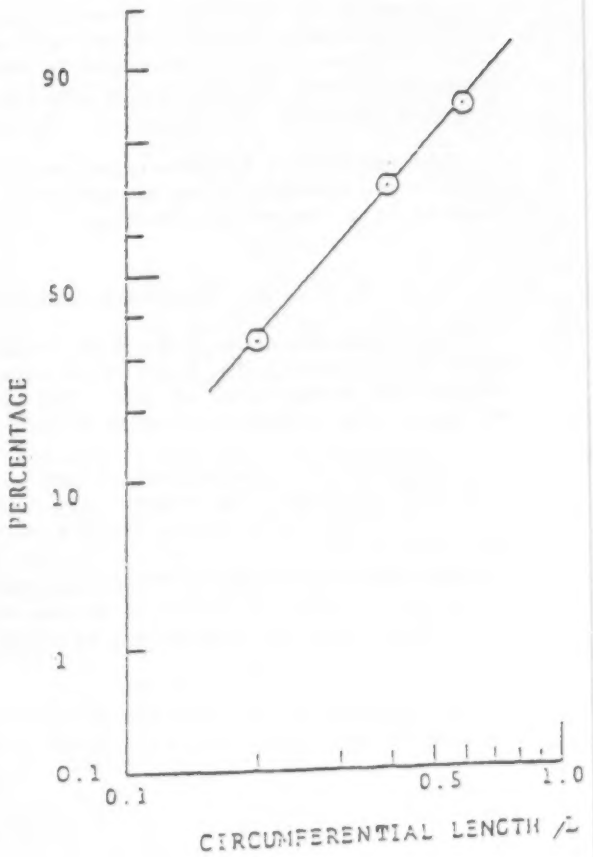

Fig.3

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Annex II

IN-SITU OBSERVATION OF ORBITAL DEBRIS USING MILLIMETRE-WAVE RADAR

by

Yoshiaki Suzuki, Chief, Space Communication Systems Section,
Space Communications Division, Communications Research Laboratory,
Ministry of Posts and Telecommunications, Japan

A. Introduction

Orbital debris surveillance is very important from the standpoint of ensuring the safety of manned spacecraft. The Space Surveillance Network (SSN) of the United States of America has been surveying these objects routinely and using the data to eliminate possible risks during the launching of artificial satellites or space shuttles.

However, ground-based observation has a limited ability to detect small debris at high altitudes due to limited antenna gain, limited transmitting power of the radar and the effect of atmospheric absorption. Therefore, distribution data for comparatively small debris are lacking. It is desirable to observe smaller debris directly in orbit.

As one method for observing smaller debris, an experiment on debris observation using millimetre-wave radar on the Space Station is proposed and studied in a preliminary manner.

B. Observation experiment at the Space Station

The experiment is to be done using the Exposed Facility (EF) of the Japanese Experiment Module (JEM) with an antenna assembled by a manipulator attached to Pressurized Module (PM) of JEM. The antenna assembly experiment is being studied as one of the reference mission models for Japanese space station experiments.

Figure 1 is a conceptual illustration of the millimetre-wave radar with the assembled antenna. The antenna and transmitter/receiver are mounted on a steerable gimbal platform attached to the tip of a mast which can be moved from its assembly position to the position at the end of EF in order to obtain a wide-angle view for various application experiments, including the millimetre-wave radar.

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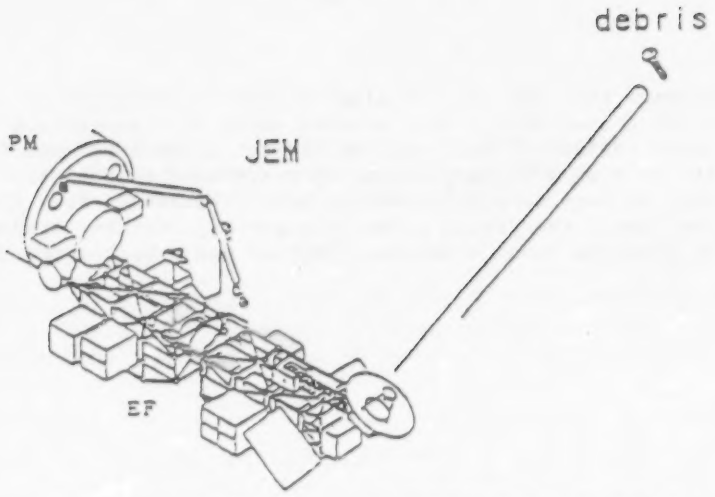

Fig. 1 Conceptual figure of the millimetre wave radar.

The purpose of the experiment is to observe the small-debris (less than 1 cm) distribution at the altitude of the Space Station. The table below shows proposed principal characteristics for the radar.

Proposed principal characteristics of millimetre-wave debris radar

Transmitting frequency	36 GHz
Antenna diameter	2 m
Pulse frequency	20 kHz
Transmitting power	5 kw
Pulse width	100 nsec

Using the above parameters, the maximum detection range for 5-mm diameter debris can be calculated to be about 7 km using the radar equation. At a range of 7 km, the frequency of detection of any debris larger than 5 mm in diameter is estimated at about 7 times/year without moving the antenna beam.

By sweeping the beam, the frequency of detection can be increased. However, there is a restriction on the beam sweep angle due to limitations on the speed of beam change, which depends on the transmitting pulse period and the performance of the phase switching device.

Assuming the use of ferrite-type phase switching devices, it is possible to sweep over an angle of about six times the beam width. In this case, the detection frequency will be more than 40 times/year.

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It is expected that the data obtained by the millimetre-wave radar will be used to establish a statistical debris model which will contribute to the design of shields for space vehicles. Moreover, if the orbits of space debris are determined, the data will be very useful in preventing collisions. For this purpose, it will be necessary to calculate orbital elements from the position, speed and direction of the debris. For this purpose, further studies should be carried out to give the radar a Doppler function and a high-speed tracking capability.

Annex III

OPTICAL OBSERVATION OF GEOSTATIONARY ORBITING OBJECTS USING A 1.5-MILLIMETRE TELESCOPE SYSTEM WITH A LOW-NOISE CHARGE-COUPLED-DEVICE CAMERA

by

Yoshinori Arimoto, Senior Research Officer, Space Technology Section, Space Communications Division, Communications Research Laboratory, Ministry of Posts and Telecommunications, Japan

A. Introduction

The geostationary orbit is one of the most valuable orbits for satellite telecommunications and Earth observations. The probability of collision between satellites located in the same part of the orbit or between geostationary orbiting debris and satellites in transfer orbit has been considered to be negligibly small. However, in the near future, the possibility will increase as the satellite population grows. Therefore, technological development for monitoring geostationary orbiting objects is important.

An optical ground facility, the Space Optical Communication Research Centre, has been constructed at the Communications Research Laboratory (CRL) in order to contribute to the development of technologies for optical communications and observations. The centre will be used as a fixed ground station for space optical communication experiments using a geostationary satellite (ETS-VI). In this station, a 1.5-m diameter Cassegrain-type telescope is installed to receive the laser signal from ETS-VI. The station also has a low-noise charge-coupled-device (CCD) imaging system with a liquid nitrogen cooled visible CCD camera and an image data processing computer. The performance of the CCD imaging system is shown in table 1. This system can be used effectively for monitoring geostationary objects.

The present report provides some preliminary results of optical observations of geostationary satellites using the 1.5-m telescope with the CCD imaging system.

B. Preliminary results of satellite observations

Sensitivity and tracking accuracy were measured by observing dark galaxies, stars and satellites. The lowest detectable brightness (limiting magnitude) was estimated to be about 17, with a 10-sec integration time. This value was obtained by observing the Japanese domestic geostationary satellites CS-2a and GMS-3 as shown in table 2. The apparent size caused by air turbulence, which limits tracking accuracy, was 3 to 5 arc-sec.

In the near future, the field of view (FOV) of the CCD camera will be enlarged to improve detectability of geostationary objects. The minimum detectable size of

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such objects is estimated to be smaller than 20 cm in diameter, based on table 2 and the effective cross-section of geostationary satellites.

C. Conclusion

It turned out to be quite easy to track geostationary satellites using the CCD imaging system whenever the sky was clear at night. In the near future it will be possible to detect geostationary objects whose minimum size is about 20 cm in diameter. The system can be used effectively to survey geostationary objects, such as operational and retired satellites and debris.

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Table 1. Performance of the Cooled CCD Camera

- CCD (GEC Hirst Research Lab., England, P8600 device)
  Three Phase CCD, Frame Transfer
  385 × 578 pixels (8.5 × 12.7mm), 22 × 22 μm^2 each
- Performance

Response Wavelength:		0.58 ~ 0.92 μm (λ c 0.75 μm)
Operational Temperature:		140 K
Peak Quantum Efficiency:		0.5
Read-out Noise (r.m.s):		7.8 ± 0.69e
FOV:	Present:	64.7" × 97.2"
	Enlarged:	256" × 384"
Over All Sensitivity:		0.2 counts/photon

Table 2. Brightness of a Geostationary Satellite and Estimated Limiting Magnitude

	Magnitude	Integration time
Observed magnitude of "CS-2a"	14.1	5 sec
Limiting Magnitude		
Present:	15.0	1 sec
	16.8	10 sec
Future:	17.5	1 sec
	19.5	10 sec

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Annex IV

ACTIVITIES OF THE NATIONAL SPACE DEVELOPMENT AGENCY ON SPACE DEBRIS

by

Dr. Masanori Homma, Director, Research and Development, Planning Division, Programme Planning and Management Department, National Space Development Agency, Japan

A. Introduction

Space debris consists of both meteoroids and artificial objects such as dead satellites, rockets, particles, paint flakes, etc. Recently, the problem of space debris has come to be regarded as very important because the impact of space debris could be fatal to astronauts, and the probability is increasing with the expansion of human activity in space. Furthermore, the probability of collisions with satellites is increasing with increases in satellite lifetime and size. From the point of view of collision probability, low-Earth orbit is more dangerous than geosynchronous orbit. The proportion of artificial objects among space debris is becoming larger than that of meteroids. In particular, at the altitude of the Space Station, i.e. 400-500 km, artificial objects are already dominant. As for meteroids, they increase seasonally when the Earth passes through regions where tiny particles are dense. The Perseids meteor stream in August is a famous example.

The activities relating to space debris are classified into the following three areas: observation of space debris; measures to avoid generation of space debris; and protection of satellites from collision with space debris. Observations are not conducted routinely in Japan, and we depend on the United States of America for those data. However, the two latter activities are conducted in Japan.

In addition to the space debris problem, other problems occur in space; for example, the emission of radiation from nuclear-powered satellites disturbs the gamma-ray observation satellite. Comprehensive countermeasures will thus be required against "space pollution", which includes not only space debris but also other environmental obstacles in space.

B. Measures for launch vehicles

When an upper stage explodes at a high altitude, a great deal of particles are scattered in space. United States Delta rockets demonstrated this when their fuel tanks exploded due to residual propellant. To prevent such explosions, the National Space Development Agency (NASDA) takes the measures indicated below for the second stage of the H-I rocket, which is operational in Japan. The same measures will also be taken in the second stage of the H-II rocket, which is now under development.

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1. Venting the residual propellant in tanks

There remains propellant amounting to 3 per cent of full load in the second stage tanks at the engine cut off. This is released through engine chill-down lines by opening the valve to space for several hundredths of a second. Even after this venting, there still remains some propellant, and its evaporation increases the tank pressure. But this pressure is controlled at below the upper limit by a mechanical relief valve in order to prevent explosion. (See 1, 2 in Fig. 1.)

2. Venting the helium gas in bottles

The residual helium gas in the ambient temperature bottles is vented naturally through a purge line, so there are no special measures required. However, the helium gas in the cryogenic temperature bottles is released through the liquid oxygen (LOX) tank pressurization line into the LOX tank. This helium gas increases the tank pressure, but its pressure is kept below the limit by the tank relief valve mentioned above. (See 3, 4 in Fig. 1.)

3. Depletion burning of the gas jet propellant

After the end of second stage operation, the residual propellant for the gas jets (hydrazine) is depleted by firing the thrusters for about 1/500 second. (See 5 in Fig. 1.)

C. Measures in satellites

1. Deorbiting geostationary satellites

To prevent collisions between operational satellites and dead satellites in geosynchronous orbit, NASDA has carried out deorbiting manoeuvres for satellites at the end of their life. For example, the CS (Communication Satellite) was deorbited 400 km above the geosynchronous orbit in November 1988, GMS-2 to an orbit 200 km higher in November 1987. NASDA will continue deorbiting in the future providing that propellant is left in the satellite.

2. Miscellaneous

NASDA has decided to install a bolt catcher in ETS-VI to catch the separation bolt for the deploying solar paddle so that it does not fly away.

D. Measures in the Japanese Experiment Module

Because the Japanese Experimental Module (JEM) must be as protected against space debris as other modules of the Space Station, the design requirements of the National Aeronautics and Space Administration (NASA) have been adapted for JEM as

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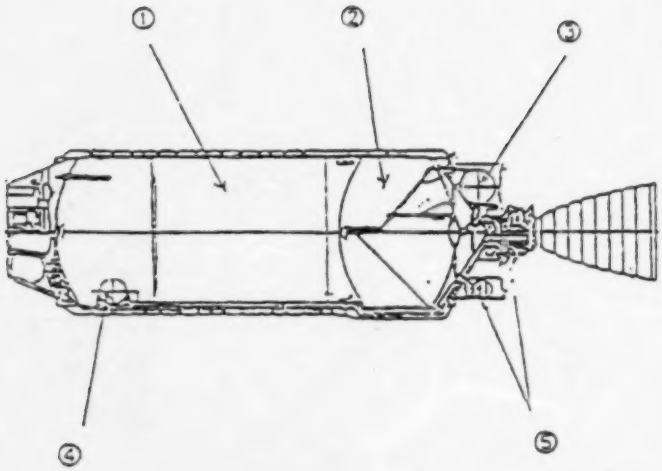
well. In order to determine the required data concerning space debris, it is necessary first to design JEM. At the altitude of the Space Station, space debris is increasing yearly as space activities grow. The safety requirements of JEM should be determined with respect to this environment. A mathematical model of space debris has been developed for the design of JEM. For the protection of JEM, a bumper will be used. Some basic experiments have been carried out to obtain data concerning the characteristics of the structure and material for the bumper. However, it is difficult to accelerate particles up to the speed of space debris for purposes of simulation. The development of test equipment itself is a problem.

The present configuration of the JEM bumper is shown in figure 2; it is a double barrier of aluminium installed on the external wall of the pressurized module. In colliding with the outer barrier of the bumper, high-speed debris will melt and spread and be stopped by the inner barrier. The thermal insulation material between the barrier and wall is also effective for protection. In general, most collisions with space debris will occur in the forward-facing area of the Space Station. The velocity range of debris in the design criteria is 4 km/s. NASDA has developed plans for a rail gun for this velocity range. Hyper-speed collisions at about 10 km/s are beyond the capability of present equipment and technology. We are now planning to use aluminium as the material for the bumper, but we are still investigating the feasibility of other materials, such as Kevlar or ceramics.



① Residual Propellant: LH2

② Residual Propellant: LOX

③ Room Temperature Helium Gas

④ Cryogenic Temperature Helium Gas

⑤ Residual Hydrazine

Fig.1 Hazardous Elements of Explosion in Second Stage of H-I Rocket

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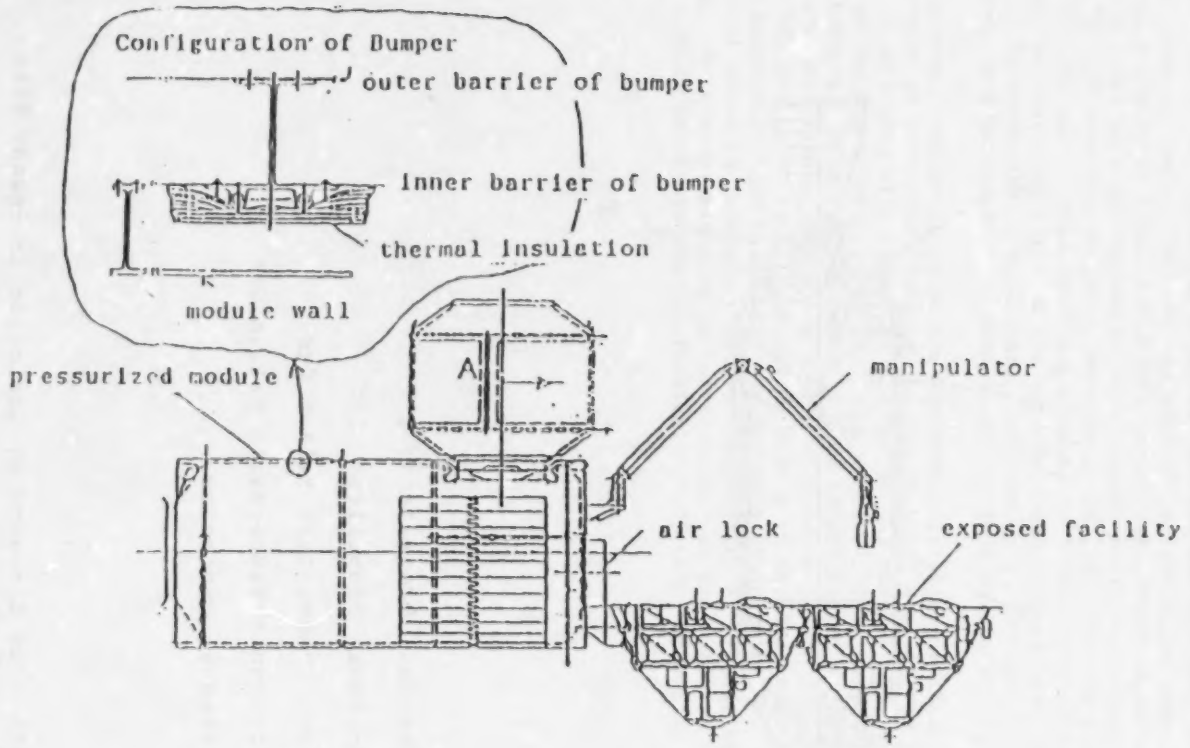

Fig. 2 Configuration of JEM and its bumper

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Note by the Secretariat

Addendum

Union of Soviet Socialist Republics: working paper

Research into collisions between spacecraft carrying nuclear power sources (NPS) and space debris, and their possible consequences, is of enormous importance in radiation protection. This is because after a collision the trajectory parameters of the NPS-carrying spacecraft (or, if the spacecraft is destroyed, the various pieces of it) and the length of time before the NPS enters the dense layers of the atmosphere may change. Any evacuation of the possible radiation effects of a collision must take account of the particles of radioactive material and pieces of the NPS that will fall after the burn-up of the spacecraft and NPS or individual pieces of them.

For this purpose, spacecraft-borne NPSs are regarded as power reactors and radioisotope thermoelectric generators launched as part of a spacecraft configuration into a sufficiently long-lived earth orbit to allow radioactivity in the NPS to decline to safe levels.

Collisions may involve:

1. Nuclear power reactors (NPRs) with disposal systems

2. Fuel element assemblies ejected from the reactor vessel in the disposal orbit

3. Nuclear power reactors configured into spacecraft

4. Spacecraft carrying radioisotope thermoelectric generators (RTGs)

5. Other spacecraft of various kinds

6. Man-made fragments larger than 1 cm in size.

The basic parameters (mass and dimensions) of objects which might be involved in a collision are shown in table 1.

Table 1

Object	Mass (kilograms)	Length or characteristic dimension (millimetres)	Diameter (millimetres)
NPR + disposal system	1 250	5 800	1 300
Fuel element assembly	53	600	200
Configured-in NPR	3 800	10 000	1 300
Satellites	5 000	5 000	3 000
Fragments	0.005	10	-
	0.3	40	-
	5.0	100	-

Table 2 shows the orbital parameters of NPRs plus disposal systems and NPRs configured into spacecraft launched by the USSR: spacecraft designation, date of launch, boost date and disposal orbit. All objects are in orbits at an inclination of roughly 65 degrees. Beginning with satellite Cosmos-1735, in addition to the disposal orbit for the NPR plus disposal system, table 2 gives for illustrative purposes the orbit of the fuel element assembly if it were ejected backwards from the reactor vessel after the firing of the second booster thrust.

Table 2

Satellite designation	Launch date	Boost date	Launch or disposal orbit (kilometres)	
			Perigee	Apogee
Cosmos-367	3 Oct. 1970	3 Oct. 1970	915	1 040
Cosmos-402	1 Apr. 1971	1 Apr. 1971	945	1 032
Cosmos-465	25 Dec. 1971	5 Jan. 1972	930	1 027
Cosmos-516	21 Aug. 1972	25 Sept. 1972	910	1 036
Cosmos-626	27 Dec. 1972	10 Feb. 1974	912	978
Cosmos-651	15 May 1974	25 July 1974	891	947
Cosmos-654	17 May 1974	30 July 1974	908	1 024
Cosmos-723	2 Apr. 1975	15 May 1975	903	960
Cosmos-724	7 Apr. 1975	21 July 1975	854	945
Cosmos-785	12 Dec. 1975	12 Dec. 1975	887	1 026
Cosmos-860	17 Oct. 1976	10 Nov. 1976	927	993
Cosmos-861	21 Oct. 1976	20 Dec. 1976	914	1 004
Cosmos-952	16 Sept. 1977	7 Oct. 1977	906	996
Cosmos-1176	29 Apr. 1980	10 Sept. 1980	876	961
Cosmos-1249	5 Mar. 1981	19 June 1981	896	988
Cosmos-1266	21 Apr. 1981	29 Apr. 1981	919	937
Cosmos-1299	24 Aug. 1981	5 Sept. 1981	907	983
Cosmos-1365	14 May 1982	27 Sept. 1982	893	983
Cosmos-1372	1 June 1982	10 Aug. 1982	924	961
Cosmos-1412	2 Sept. 1982	10 Nov. 1982	893	993
Cosmos-1579	29 June 1984	27 Sept. 1984	900	986
Cosmos-1607	31 Oct. 1984	1 Feb. 1985	931	971
Cosmos-1670	1 Aug. 1985	22 Oct. 1985	927	1 012
Cosmos-1677	24 Aug. 1985	23 Oct. 1985	939	941
Cosmos-1736	21 Mar. 1986	21 June 1986	950	1 022
			949	1 002
Cosmos-1771	20 Aug. 1986	15 Oct. 1986	992	996
			910	981
Cosmos-1818	2 Feb. 1987		790	810
Cosmos-1860	19 June 1987	28 July 1987	930	1 000
			930	970
Cosmos-1867	10 Jul. 1987		797	813
Cosmos-1900	12 Dec. 1987	30 Sept. 1988	722	770
			718	765
Cosmos-1932	14 Mar. 1988	21 May 1988	947	1 019
			937	977

An NPS plus disposal system will have a disposal orbit lifetime of at least 300 years, which is long enough for Uranium-235 fission products to decay to radioactivity levels of less than 0.1 Curie (by reference to Caesium-137).

A fuel element assembly will have a disposal orbit lifetime of at least 430 years. Configured-in NPRs, and the Cosmos-1818 and 1867 satellites will remain in their working orbits at least 360 years. In the case of Cosmos-1900, the NPR plus disposal system without the fuel element assembly has an orbit lifetime of around 200 years (30 years is plenty), and the fuel element assembly, over 300 years.

Cosmos-84 and Cosmos-90, launched by the USSR in 1965 into a 1,500-kilometre-high orbit, are carrying RTGs containing the radioactive isotope Polonium-210. By 1990, the isotope had been decaying for 25 years; the residual activity of the Polonium-210 does not exceed 10-16 Curies, meaning there is no radioactivity present.

Table 3 gives the orbital parameters of spacecraft carrying Plutonium-238 RTGs launched by the United States: satellite designation, launch date and orbit parameters, and disposal orbit lifetime.

Table 3

Satellite designation	Launch date	Orbit (kilometres) Perigee	Apogee	Orbit inclination (degrees)	Orbit lifetime (years)
Transit 4A	29 June 1961	890	1 000	67.5	500
Transit 4B	15 Nov. 1961	960	1 130	32.4	1 200
Transit 5BN-1	28 Sept. 1963	1 090	1 150	89.9	1 900
Transit 5BN-2	5 Dec. 1963	1 080	1 110	90.0	1 800
Nimbus 3	14 Apr. 1969	1 070	1 131	99.9	3 600
Nimbus 4	8 Apr. 1970	1 085	1 098	99.7	3 600
Triad	2 Sept. 1972	716	863	90.1	137
Nimbus 5	11 Dec. 1972	1 087	1 100	99.5	3 600
Nimbus 6	12 June 1975	1 099	1 112	99.6	3 600

For the purposes of investigating the consequences of collisions with space debris, the altitude of possible collisions should be taken to be in the range of 800 to 1,100 kilometres: This is where all the nuclear sources, together with a fairly large number of other satellites and the maximum density of space debris, are to be found. The number of objects in orbits at altitudes between 800 and 1,100 kilometres is as follows:

NPR plus disposal system	29
Without fuel element assembly	16
Fuel element assembly	16
Configured-in NPR	2
Satellite with RTG	9
Other satellites	c.500
Fragments larger than 1 cm	$6 \times 10^{-8}/km^3$
Fragments larger than 4 cm	$10^{-8}/km^3$

In orbits at altitudes between 800 and 1,100 kilometres, object velocity is between 7.45 and 7.35 km/second. The orbital precession rate for an inclination of 65° is 2.7°-2.5°/24 hours, and for an inclination of 100° is 1.15°-1.0°/24 hours. Angles of impact may range between 0° and 130° for orbits with an inclination of 65°, and from 0° to 180° for orbits with an inclination of around 100°.

The consequences of a spacecraft with an on-board NPS colliding with space debris can be studied in a variety of collision models. Table 4 shows the collision models assumed, collision conditions and the possible results.

Studying the possible effects of collisions according to a variety of interaction models will require methods to be developed for calculating the effects in the event of elastic and non-elastic impacts, and of spacecraft destruction and the scattering of secondary fragments.

The findings of the investigations being conducted in the USSR will be submitted for discussion to the Scientific and Technical Sub-Committee of the United Nations Committee on the Peaceful Uses of Outer Space.

Table 4

Model	Collision conditions	Result
NPR + disposal system (spacecraft + NPS) collides with fragment	Small angle of impact	Bounces off
	Large angle of impact, impact at centre of mass	Goes straight through
		Penetrates and stops
	Large angle of impact, impact on peripheral area	Pieces of spacecraft and NPR, eg. reactor body, break off
NPR + disposal system (spacecraft + NPS) collides with another satellite	Small angle of impact	Bounces off
	Large angle of impact, impact at centre of mass	Coalesce
	Large angle of impact, impact on peripheral area	Spacecraft and NPR destroyed, pieces scattered
Fuel element assembly collides with satellite	Small angle of impact	Bounces off: assembly breaks up into individual elements and pieces of element
	Large angle of impact, impact at centre of mass	Goes straight through: pieces of element fly off
		Penetrates and stops
	Large angle of impact, impact on peripheral area	Destroyed and secondary fragments scattered
Fuel element assembly collides with fragment	Small angle of impact	Assembly breaks up into individual elements and pieces of element
	Large angle of impact	Destroyed and secondary fragments scatter

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2 March 1990

ARABIC, CHINESE AND ENGLISH ONLY

COMMITTEE ON THE PEACEFUL USES OF
OUTER SPACE

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Note by the Secretariat

Addendum

Union of Soviet Socialist Republics: working paper

Corrigendum

1. Page 1, line 3

   For "protection" read "safety"

2.* Page 1, line 6

   For "evacuation" read "evaluation"

3. Page 2, line 4 from the bottom

   For "Cosmos-1735" read "Cosmos-1736"

4. Page 2, line 2 from the bottom

   For "assembly if it were ejected" read "assembly ejected"

5.** Page 4, paragraph 3, line 4

   For "10-16 Curies" read "10^{-16} Curies"

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* Not applicable to the Arabic and Chinese text.

** Not applicable to the Chinese text.

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A/AC.105/C.1/WG.5/L.24/Add.3
28 February 1990

ORIGINAL: ENGLISH

COMMITTEE ON THE PEACEFUL USES OF
OUTER SPACE
Scientific and Technical Sub-Committee
Working Group on the Use of Nuclear Power
Sources in Outer Space

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Note by the Secretariat

Addendum

FEDERAL REPUBLIC OF GERMANY

Following the research reported last year by the Federal Republic of Germany to the Working Group on the Use of Nuclear Power Sources in Outer Space, 1/ research on orbital debris in the Federal Republic of Germany has continued, particularly on the subjects of the long-term evolution of the debris population, including the problem of fragment generation by collisions; 2/, 3/ the possibilities of protective shielding measures; 4/ and collision avoidance manoeuvres. 5/

The text annexed hereto is a summary review of the results of the above-mentioned recent research. 6/

Research in the field of space debris will continue in the future on such topics as modelling of the population of small objects in Earth orbit, advance shielding concepts that take account of mutual shadowing effects, collision chain reactions and techniques for the removal of debris from orbit.

Notes

1/ A/AC.105/C.1/WG.5/L.21/Add.6.

2/ Rex, D., P. Eichler, U. Soppa, J. Zuschlag and A. Bade. Space Debris - Origin, Evolution and Collision Mechanics. Thirty-ninth Congress of the International Astronautical Federation, Bangalore, India, October 1988, Paper No. 88-520.

3/ Eichler, P., and D. Rex. Chain Reaction of Debris Generation by Collisions in Space - A Final Threat to Space Flight? Fortieth Congress of the International Astronautical Federation, Malaga, Spain, 7-13 October 1989, Paper No. IAA-89-628.

4/ Eichler, P., and D. Rex. Collision Risk in Space - Detailed Analysis and Basic Consequences for Design and Operation of Larger Structures. CNES International Symposium on Space Dynamics, Toulouse, France, 6-10 November 1989, Paper No. MECSPA CNES 89/157.

5/ Bendisch, J., and D. Rex. Analysis of Orbital Manoeuvres of a Large Space Structure to Avoid Collisions with Space Debris. CNES International Symposium on Space Dynamics, Toulouse, France, 6-10 November 1989, Paper No. MECSPA CNES 89/159.

6/ The text is being circulated as received, in the language of submission only (English).

ANNEX*

I. SPACE DEBRIS - ORIGIN, EVOLUTION AND COLLISION MECHANICS

Abstract

The number of man-made objects orbiting the earth and the corresponding collision risk has become a concern, which deserves thorough investigation. In addition to the 3 500 objects launched and presently still in orbit, about 10 to 20 times as many debris particles down to 1 cm in size have been produced in earth orbits by unintentional and intentional break-ups. The number and orbital data of the majority of these smaller debris particles cannot be determined by tracking. So a complete mathematical analysis of nearly all 90 reported break-ups has been performed, generating the numbers of fragments, their mass- and mass/area-distribution and their orbits. This simulation also includes the variation of all orbits with time, especially the descent and removal of objects by atmospheric drag and lunisolar pertubations. On the base of this data bank scenarios for the future development of space debris and collision probabilities are derived, showing that the highest accumulation of debris presently at an altitude of 800-1 000 km, will shift to 1 400 km on the long term. Collision risk and -geometry is determined by a deterministic model which can also be used to design shielding.

Introduction

The possibility of overcrowding space in the near earth environment with orbiting man-made objects has been recognized as a real problem which already influences space missions now and may well become a major aspect of future space flight in general. An example of direct influence is the shielding of all manned modules required in the space station programme, and the general importance is taken into account by the institution of space debris working groups within ESA and NASA. Present assessment of the collision risk and decisions for reducing it can only be based on an incomplete knowledge of object densities, size distributions and orbital distribu-

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* This annex contains a summary of the papers referred to in footnotes 2-5 on the cover page.

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tions. So it is an urgent task to make more tracking and experimental data available on one side and on the other side to establish computer simulations which also can help to judge the future evolution of this problem. The latter is the objective of the present paper.

Composition and Origin of Space Debris

Overview

The present number of active (operating) satellites is about 350 (see Fig. 1), which would not represent any collision problem if they were the only orbital population. Also the 1 400 spent satellites, which have ended their operation but are still in orbit and the 1 750 rocket upper stages and other mission related objects still in orbit would be too small numbers to pose a problem. It is the majority of about 60 000 particles of debris which dominates the collision risk assessment. This number, which is to a large extend uncertain (values between 30 000 and 70 000 are reported) refers to objects larger than 1 cm in diameter, which are considered here, because their impact would inevitably be mortal to any satellite or space station element.

Smaller particles up to several millimeters, can be made ineffective by shielding. In order to make an assessment of the collision risk for a certain object, e. g. the space station manned modules, it would be necessary to know the abundance, size distribution and orbital distribution in space of all the objects larger than 1 cm. Unfortunately only about 7 000 of these objects are large enough (between 4 cm and 10 cm diameter) to be tracked by radar, the data of which are available thanks to the distribution of NASA/NORAD.

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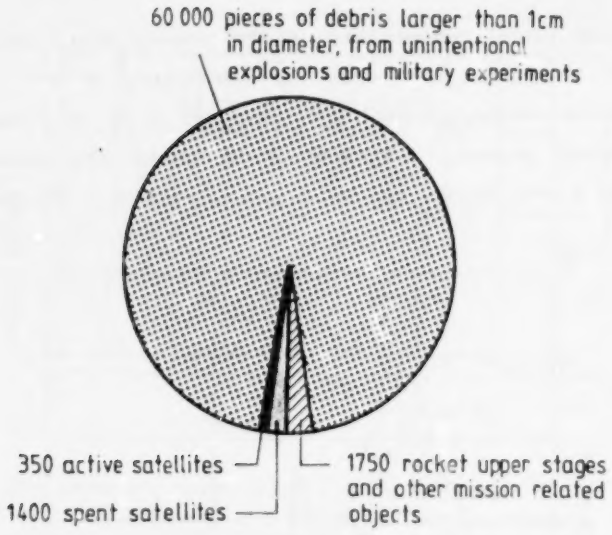
60 000 pieces of debris larger than 1cm in diameter, from unintentional explosions and military experiments
350 active satellites
1400 spent satellites
1750 rocket upper stages and other mission related objects

Fig. 1 Numbers of space flight objects presently on orbits around the earth.

Simulation of Break-ups

In view to the lack of data on objects between 1 and 5 cm size and on the basis, that the majority of these have been generated on orbit by all kinds of break-ups (low and high intensity explosions and some collisions) it was undertaken to simulate these events and the orbital evolution of their fragments up to the present time, thus creating a data bank of all objects larger than 1 cm presently on orbit. This data bank reflects the orbits of all tracked objects in a deterministic way, of all untrackable objects > 1 cm in a statistical way which is true enough for collision analyses. Out of 90 recorded break-up events between 1960 and 1988, 31 have been simulated, and they were selected such that they together account for 87 % of all break-up fragments still in orbit.

Evolution of all Objects on Orbit, Future Scenarios

Using the program ORBA, the sum of present debris object densities originating from various break-ups in the past can be generated.

/. .

Fig. 2 is a sum of all contributions to the present object density distribution. Again it is obvious, how small the contribution of the launched space objects is (NASA catalogue) and how important it is to model the mostly untrackable debri properly. According to our model, the present density of all objects has a peak at 800 km and a second peak at 1 500 km.

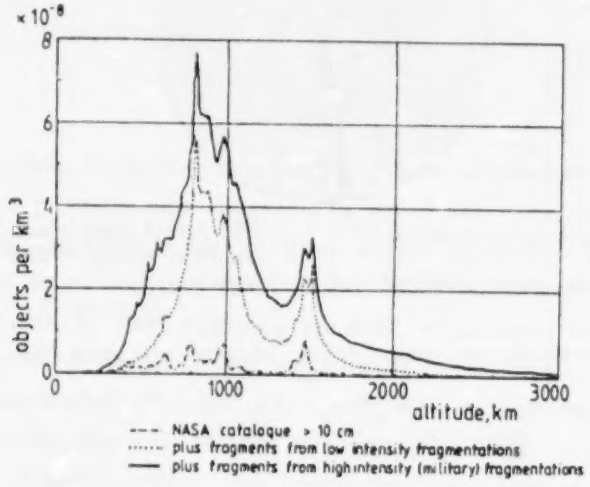

Fig. 2 Contribution of three object classes to the present density of all objects larger than 1 cm.

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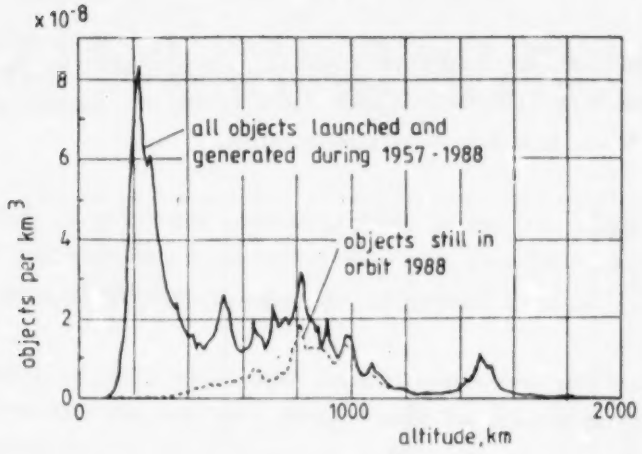

Fig. 3 The present object density (launched objects plus trackable debris > 10 cm) has been effectively reduced compared to the number of objects originally launched. This self cleaning effect due to air drag is effective up to about 1 000 km altitude.

Fig. 3 shows, how effective the self cleaning effect of the earth's atmosphere is. The solid line shows the object density in 1988 if no descent and removal of objects had taken place since the beginning of space flight, compared to the actual density distribution (dashed line). A very large peak at about 220 km has been completely eliminated by the atmospheric braking effect, and the densities are lowered up to about 900 km altitude. Now the model can be used to predict trends for the future. It is assumed that the future orbital distribution (inclinations, eccentricities, semi-major axis) of launched objects will be the same as in the past, due to the geographical locations of launching places and to the mission types. In Fig. 4 we assume a 3 % yearly increase in launches of payloads and mission related objects and the generation of 500 fragments (from one break-up) per year. In this and in the following simulations, only objects of trackable size (larger than 5 cm) are included. Under these assumptions, and of course including the orbital descent of the objects according ot their individual ballistic coefficients and the elimination from orbit, it is found that after 20 years the number increased (from 7 000 now) to 18 000 and after 46 years to 33 000. During the same time span, the density peak which is now at 800 km altitude will

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shift to 1 000 km and finally to 1 500 km, as is visible in Fig. 4. This is an indication, how vulnerable higher earth orbits are against contamination with space debris in a long term consideration.

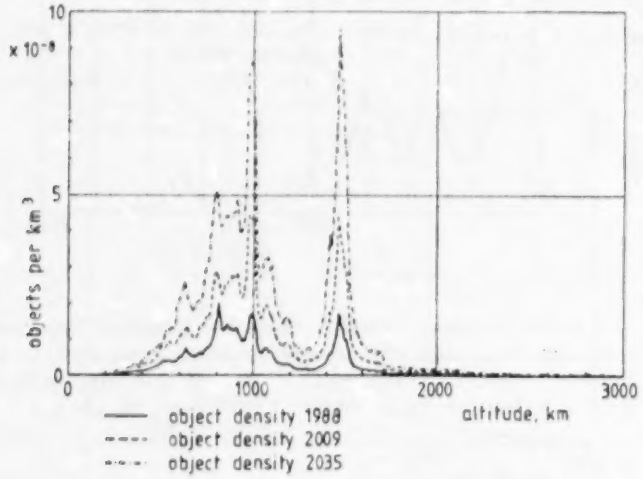

Fig. 4 Future evolution of trackable object density (> 10 cm) versus altitude.
Assumption: 3 % yearly increase in launches of payloads and mission related objects plus one explosion (500 trackable fragments) per year.

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II. COLLISION RISK IN SPACE - DETAILED ANALYSIS AND BASIC CONSEQUENCES FOR DESIGN AND OPERATION OF LARGER STRUCTURES

Abstract

The number of man-made objects orbiting around the earth has become so high that collision risks have to be taken into account in the mission planing and operation of spacecraft, especially of manned vehicles.

First results of detailed collision investigations are presented, which have been gained with the help of a deterministic calculation procedure taking the orbital mechanics of every object in earth orbit into consideration. In the course of this, it was possible to establish a high dependence upon the angle of the object flux in the near earth environment. The two-dimensional character is especially to be emphasized here, i. e. all objects colliding seem to come from a form of debris plane which is perpendicular to the orbital plane.

Through skilful selection of the structure and attitude orientation of larger structures, this property can be made use of the reduce the object flux and thus the necessary shielding. For this, the varying attitude orientations of a cylinder, which corresponds to the COLUMBUS in free flight, the MTFF or the Polar Platform, are investigated. Also, various structures and flight attitudes of 4 cylinder are treated, as they are planned for the International Space Station. Thus, the collision risk can be reduced by more than half by rotating the attitude in flight by 90 degrees. Finally, principal statements concerning the extension of the Space Station are given.

1. Body fixed coordinate system for the representation of the angles of collision

In order to establish the angle below which a collision takes place, the body fixed coordinate system shown in Fig 5 is used. This earth-orientated system of coordinates is to be made clearer by means of the aircraft which has been drawn in. The x-axis points in the direction of flight, the z-axis in the direction of one wing and the y-axis vertically "upwards" in the direction of space. The two collision

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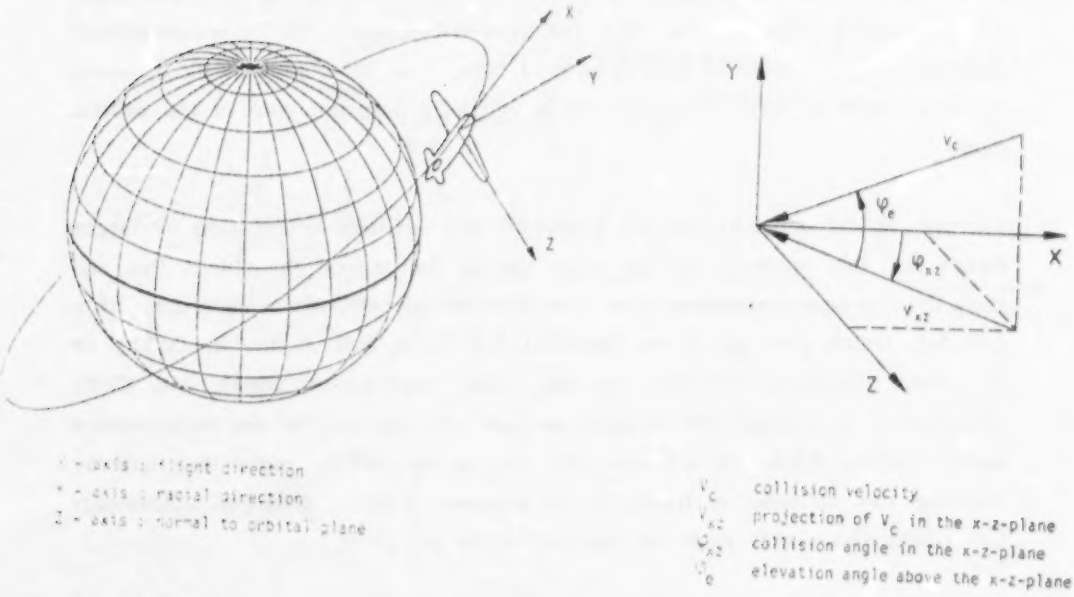
angles φ_e and φ_{xz} show below which relative angle the colliding object hits our imaginary aircraft.

These angles of collision result, as can be seen on the right-hand side of Fig. 5, from the projection of the relative velocity which comes about in the collision, to the horizontal plane (x-z plane). If the object flux above the respective angle of collision is now summated, we are given the object flux as a function of the respective angle in space.



X - axis : flight direction
Y - axis : radial direction
Z - axis : normal to orbital plane

V_c collision velocity
V_{xz} projection of V_c in the x-z-plane
φ_{xz} collision angle in the x-z-plane
φ_e elevation angle above the x-z-plane

Fig. 5 Body fixed coordinate system to indicate the collision angles φ_e and φ_{xz}

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1.1 Object flux as a function of the angle in the orbital plane (x-y plane)

For reasons of orbital mechanics, all colliding objects meet below very small elevation angles φ_e. The object flux therefore has a very strongly two-dimensional character. All colliding objects seem to come practically from one single plane, the x-z plane perpendicular to the orbital plane. This so-called debris plane corresponds to the wing plane of our imaginary aircraft, e. g. the horizontal plane.

1.2 Object flux as a function of the angle in the x-z plane

There is also a strong dependence of the object flux within the debris plane (x-z plane) upon the angle observed (φ_{xz}) for reasons of orbital mechanics. The object flux not only depends on the altitude, but mainly on the inclination of the target orbit.

For targets in low inclined orbits, e. g. 28.5 degrees for the ISS, the greatest object flux comes about between 45 and 75 degrees and -45 and -75 degrees, respectively, as shown in Fig. 6a. Hardly any collisions are to be expected from head-on (degree of aperture ± 30 degrees), and hardly any are to be expected from the back. To put it clearly, this means that most of the objects within the debris plane, i. e. the wing plane of our aricraft, come diagonally from the left or the right.

For higher target inclinations, more and more lower collision angles will occur within angles of ± 30 deegrees, as shown in Fig. 6b. But besides the angular distribution, the total object flux depends on the inclination of the target orbit. Smaller collision angles are leading to higher collision risks at the orbital intersections, so that the total flux at 90 degrees inclination is about 6×10^{-6} per m^2 and year compared to 4×10^{-6} at 28.5 degrees.

/...

1.3 Object flux on areas with varying orientations perpendicular to the debris plane

The object flux on the surface of a sphere with a cross sectional area of 1 m^2 at an orbital altitude of 500 km and an inclination of 28.5 degrees is about 4×10^{-6} per year (cf. Chap. 1.2). If there were an isothropic object flux, the object flux per m^2 of surface would be exactly one quarter, i. e. 10^{-6} per year. But, as was shown in the previous chapter, the object flux is strongly dependent upon the angle, which means that each surface will be subjected to quite different fluxes, depending upon its attitude orientation. If an average is made of all possible orientations, then the average flux F_m is naturally again 10^{-6} per year.

The actual object flux on a surface perpendicular to the debris plane results from the integration of the object flux as a function of the angle from Fig. 6 with the cosine of the angle between the surface normal and the respective angle of collision φ_{xz}. Fig. 7 shows the flux on the front of a panel as a function of the angle β between the surface normal and the direction of flight x for target inclinations of 28.5 and 90 degrees, respectively. The object flux is relative, as a flux factor, to the average flux F_m of 10^{-6} at 28.5 degrees and 1.5×10^{-6} at 90 degrees inclination.

If the surface is not perpendicular on the debris plane, this angle of inclination enters the object flux once again with the cosine. Surfaces parallel to the debris plane thus receive practically no object flux.

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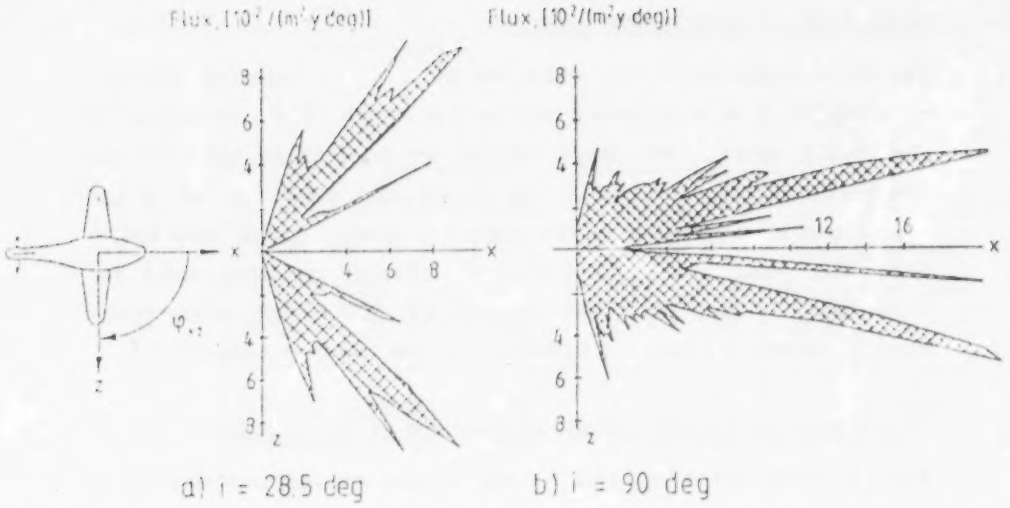

Fig. 6 Object flux as a function of the collision angle φ_{xz} for different target inclinations (h = 500 km)

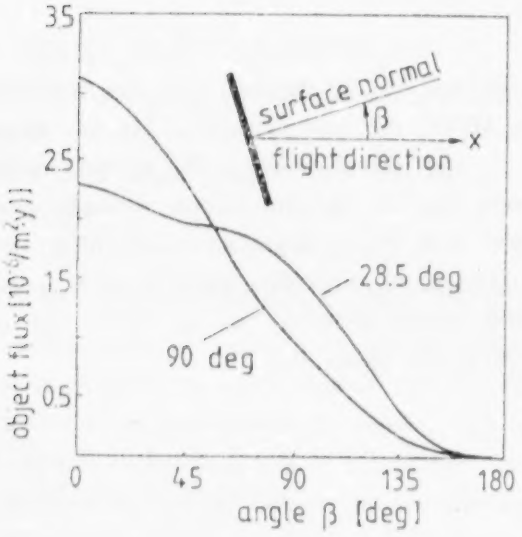

Fig. 7 Object flux as a function of the angle β (target inclinations 28.5 and 90 degrees)

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2. Object flux on a cylindrical module

The basic components from which the ISS is to be built are cylindrical modules, 4 m in diameter and 12.7 in length. This corresponds to the loading area of the Space Shuttle, which is to be used for the transportation into space. For this reason, the investigations on the object flux as a function of the angle are carried out on such cylinders. The results for one individual cylinder are thus valid for COLUMBUS in free flight and also for the MTFF. The entire Space Station, which consists of 4 cylinders, is dealt with in Chapter 2.2.

2.1 Object flux for various attitude orientations of the cylinder

Tabel 1 shows the object flux for the 3 basic attitude orientations of the cylinder for target inclinations of 28.5 and 90 degrees, respectively. It can be established that the lateral and longitudinal cylinder, the longitudinal axes of which are in the debris plane, are generally more favourable than the vertical cylinder perpendicular to the debris plane.

For a target inclination of 28.5 degrees, e. g. for COLUMBUS in free flight or for the MTFF, the most favourable attitude of an individual cylinder is that of the lateral cylinder. The vertical cylinder has, in comparision, simply due to its unfavourable attitude orientation, an 31 % higher object flux. For a target inclination of 90 degrees, e. g. for the Polar Platform, the most favourable attitude is the longitudinal cylinder. The lateral cylinder has an 58 % and the vertical cylinder an 101 % higher object flux.

/...

Table 1: Object flux on a cylindrical module for different attitude orientations

attitude of the cylinder (direction of the axis)	object flux F [10^{-4}/y]		ΔF to best attitude	
target inclination [deg]	28.5	90	28.5	90
lateral cylinder (z)	1.55	2.41	—	+ 58%
longitudinal cyl. (x)	1.88	1.52	+ 21%	—
vertical cylinder (y)	2.03	3.05	+ 31%	+101%

2.2 Object flux on 4 cylindrical modules

For the ISS 4 cylindrical modules are planned in the first stage of extension. For this reason, the entire flux on various structures of 4 cylinders at a target orbit of 28.5 degrees is now to be investigated more closely.

2.2.1 Object flux with free structure of the cylinders

In an unfavourable structure, i. e. without making use of the mutual shadowing effects, the total objects flux corresponds exactly to the quadruple flux on the individual cylinder. This is, for example, valid for 4 vertical cylinders on top of one another in the y direction. This most unfavourable of all structures has the highest possible object flux of $4 \times 2.03 \times 10^{-4} = 8.13 \times 10^{-4}$ per year.

The most favourable structure without shadowing effects is 4 lateral cylinders on top of one another in the y direction. Here the entire object flux is 6.20×10^{-4} per year.

/...

Through making use of the mutual shadowing effects, a much smaller object flux can be achieved. For this, the 4 cylinders must however arranged within the debris plane. The most favourable structure is that with 4 lateral cylinders successively in the x direction. This results in an object flux of 3.43×10^{-4} per year. As a contrast, the most favourable structure without shadowing effects, which consists of the same lateral cylinders, but this time outside the debris plane, has an 82 % higher object flux, the most unfavourable object flux even being 137 % higher.

2.2.2 Object flux on the rectangular structure planned for the ISS

As mentioned before a rectangular structure of the 4 modules is intended for the ISS. Table 2 shows the object flux on the basic possible attitude orientations of this structure. Once again, structures in the debris plane are favourable. In the most favourable one, the rectangular structure is lateral to the direction of flight like the individual cylinders. With an object flux of 3.72×10^{-4} per year, it is only inconsiderably worse than the most favourable free structure (cf. Chap. 2.2.1).

The flight attitude of the ISS as a longitudinal cylinder in the x-z plane is also quite good with 4.40×10^{-4} per year. The interesting thing about this is however that the most favourable flight attitude changes into the least favourable with a 118 % higher object flux, simply by being turned around the x-axis by 90 degrees.

/...

Table 2: Object flux on 4 cylindrical modules in a rectangular structure for different attitude orientations

attitude of the rectangular structure	object flux F [10^{-4}/y]	ΔF to lateral cyl. in x-z-plane
lateral cyl. in x-z-plane	3.72	--
longitudinal cyl. in x-z-plane	4.40	+ 18 %
lateral cyl. in y-z-plane	5.95	+ 60 %
longitudinal cyl. in x-y-plane	7.42	+ 99 %
vertical cyl. in y-z-plane	7.52	+ 102 %
vertical cyl. in x-y-plane	8.13	+ 119 %

In so far as the flight attitude is not pre-determined by the mission, the object flux - and thus the collision risk and the amount of shielding needed - can be considerably reduced by skilful selection of the flight attitude.

3. Summary

With the help of a deterministic method of calculation, which takes the orbit mechanics of each object in earth orbit into consideration, it was possible to establish a high dependency of the object flux in the near earth environment upon the incidence angle. The object flux, which is equivalent to the collision risk, has a strong two-dimensional character, i. e. all colliding objects seem to come from a horizontal debris plane, which is perpendicular to the orbital plane. But a strong accumulation inside this debris plane can also be seen, depending on the inclination of the target orbit.

These features can be made use of by skilful structure or attitude orientation in order to reduce the object flux and thus the shielding necessary. For an individual cylinder in low inclined orbits, which corresponds to the COLUMBUS in free flight or the MTFF, the lateral attitude in the debris plane is the most favourable. With other orientations, an object flux of up to 31 % higher can occur. For

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higher inclined orbits, e. g. for the Polar Platform, the longitudinal attitude is most favourable. Other orientations are leading here to an object flux of up to 101 % higher.

In a larger structure, such as the rectangular structure of 4 cylinder planned for the International Space Station, not only the arrangement of the cylinders is of decisive importance. The entire structure should, if possible, be arranged within the debris plane. The interesting thing about this is that the most favourable flight attitude changes into the most unfavourable, subjected to an object flux which is 118 % larger, merely by turning through 90 degrees out of the debris plane.

The further extension of the ISS should also, as far as possible, be carried out within the debris plane. Critical, manned modules should be placed on the inside and at the back, non-critical ones at the front and on the outside, In this case, the non-critical modules would shadow the critical ones, and the collision risk of the critical modules could practically be reduced to zero without any additional shielding being necessary. The upper stages of booster rockets still in orbit could, as it were, be "collected in" and installed in front of the manned modules as collision protection following a rendez-vous manoeuvre.

These first results of detailed collision investigations shown here demonstrate that great practical use can be made of this knowledge. Further investigations are however necessary, for example with regard to the actual design of shielding, taking the actual angle, mass and velocity distributions of the object flux in the near earth environment into consideration. If Europe wishes to have its own manned space flight - and the decisions in favour of COLUMBUS and HERMES appear to support his -, then Europe must learn to stand on its own feet in this, in the literal sense of the word, vital area.

III. CHAIN REACTION OF DEBRIS GENERATION BY COLLISIONS IN SPACE - A FINAL THREAT TO SPACEFLIGHT?

Abstract

The number of man made objects orbiting around the earth has already reached a level that the collision risk has become a serious consideration for all larger spacecraft. However, a far greater threat to spaceflight in general may emerge: the debris generated by collisions in space can initiate a self sustained chain reaction which could lead to the formation of an artificial debris belt. Spaceflight could then become impossible in certain altitude regions for many centuries. As a result of the detailed analysis, it was found that the population of larger space objects is of decisive importance for the fragment generation by collisions. The critical population for the setting-in of a chain reaction is only about 2 to 3 times the current population and could be reached within 20 to 50 years, if spaceflight activities will be contined as in the past. Therefore, within this time frame the number of larger space objects must be limited, e. g. by active controlled reentry manoeuvres after the end of their missions. In addition to that it could become necessary in the future to remove larger objects already in orbit, especially in the critical higher altitudes, in order to reduce an unacceptable or critical high population level.

Introduction

During only 30 years of spaceflight mankind has brought so many artificial objects in earth orbits that the danger of a collision with space debris is no longer a hypothetical problem but has become a serious threat. In the case of larger structures and longer mission-times the collision probability may amount to several percent. Besides the about 7,000 larger, catalogued objects, there of Figure 8 gives an impression of the density of occupation, there are probably 30 to 70,000 objects larger than 1 cm in earth orbits. Altogether, it has to be assumed that several hundred thousand objects larger than 1 mm are orbiting in space. In view of the high velocities in the order of 10 km/s, which occur when collisions take place, even such millimeter sized objects will penetrate the outer walls of satellites. Most of these

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objects were generated during intentional or unintentional explosions. Manned missions - including the planned International Space Station - can therefore not be realized withoud taking costly shielding measures.

However, beyond the problems of single impacts there is a far greater threat to spaceflight in general: a possible chain reaction of collisions.

The fragments generated by a collision among two larger objects in earth orbits could produce new collisions. This could successively lead to the formation of an artificial debris belt in the way of a chain reaction. Spaceflight then could become impossible in certain altitude regions for many centuries.

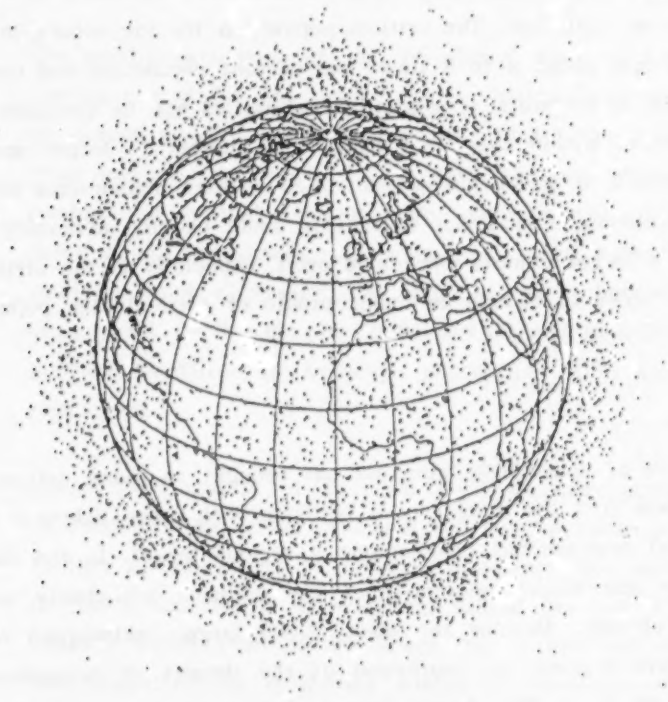

Fig. 8 Snapshot of all catalogued objects in the near earth environment as of 1989

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Basic approach

Basically there are distinct differences between the collision risk concerning one large target object and the collision risk among all objects in earth orbits concerning a chain reaction of collisions. For the collision risk concerning one large target object, e. g. the International Space Station, analysis has shown that:

- the collision risk will rise linear with the number of objects in orbit
- the sizes of other objects are negligible, for the size of the large target is dominating
- so the collision risk originates mainly from the large number of small fragments from collisions and explosions in orbit.

In contrast to this, for the collision risk among all objects it can be stated that:

- the collision risk will rise basically with the square of the number of objects in orbit
- the size of the involved objects is of great importance, for the collision risk is proportional to the square of the sum of their two diameters
- therefore the population of larger objects is of decisive importance for interactive collisions.

Analysis of the collision risk among the current population

Figure 9 shows the catastrophic collision risk among an assumend current population of 35,000 pbjects larger than 1 cm as a function of altitude. A total risk of about 3.7 % per year could be established.

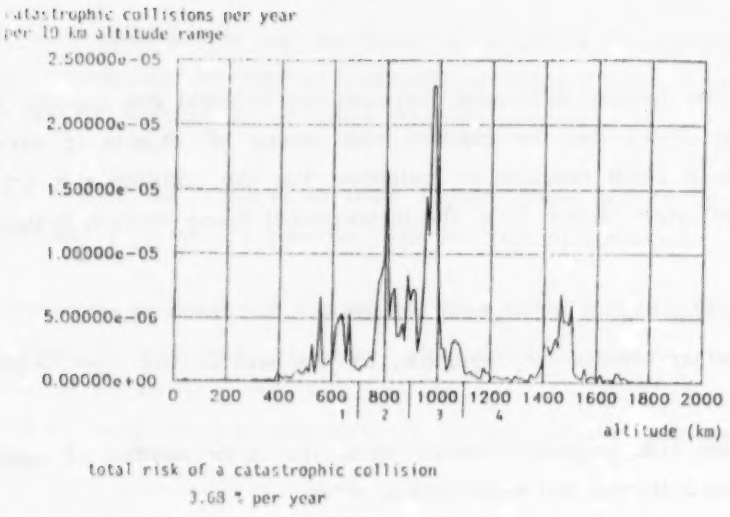

Fig. 9 Probability of a catastrophic collision as a function of the orbital altitude

The lifetime of the fragments generated by a collision will differ widely as a function of the collision altitude. To avoid an undue averaging, the catastrophic collision risk is investigated separately in 4 altitude regions:

- up to 700 km
- from 700 to 930 km
- from 930 to 1 100 km
- from 1 100 to 3 000 km.

Besides the collision velocity which in most cases was found to be in the order of 10 km/s, the most important parameters concerning the fragment generation by collision are the masses of the two involved objects. To enable a detailed analysis, the total population was divided into 3 different mass ranges

- from	1.5 g	to	1 kg	small objects
- from	1 kg	to	100 kg	medium sized objects
- more than			100 kg	large objects.

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The about 30,000 small objects are exclusively fragments from collisions and explosions in space and mission related objects, the about 1,750 medium sized objects are mainly larger fragments and mission related objects and the about 1,750 larger objects are nearly exclusively payloads and rocket upper stages.

Fig. 10 shows the results of the detailed analyses of the collision risk among the current population for the 6 types of collisions occuring among the 3 mass classes.

While the more than 600,000,000 orbit combinations are dominated by the small-small type, most of the collisions will be of the small-large type, for the collision risk is proportional to the square of the sum of the diameters of the two involved objects. A total collision risk of about 20 % per year could be established. In contrast to this, the catastrophic collisions are dominated by the medium-large and large-large collision types, because most of the small-large collisions are not catastrophic. A total risk of about 3.7 % per year for a catastrophic collision among the current population was found.

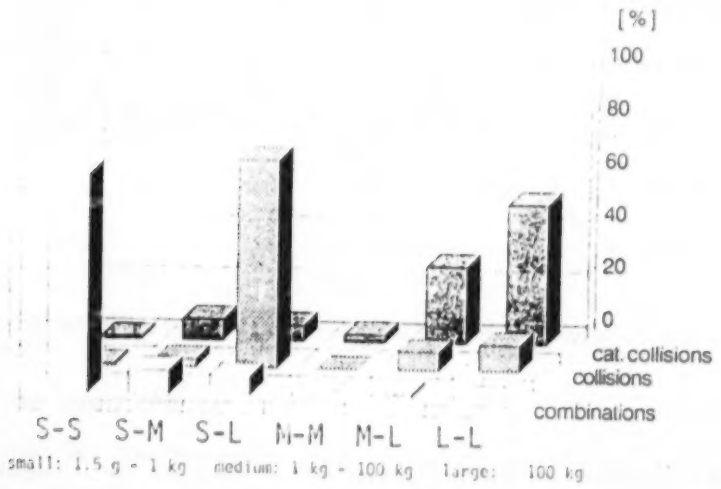

Fig. 10 Percental contribution of the different types of collisions to the collisions risk

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Analysis of possible evolutions of the population

The following chapter will present some exemplary results of simulations using the program CHAIN, to demonstrate the basic tendencies of the possible evolution of the number of objects larger than 1 cm in earth orbits.

Constant basic populations as of 1989

Fig. 11 shows the evolution of the population for an assumed constant basic population as of 1989. In addition to the basic population due to spaceflight activities, a population of about 100,000 to 150,000 collision fragments will occur within several hundred years. Therefore, the total population will tend towards an equilibrium population of about 150,000 to 200,000 objects larger than 1 cm. Although it is not realistic to assume a constant basic population as of 1989 for 3,000 years, this simulation shows that the current basic population can be classified as a stable one, i. e. will not lead to a chain reaction of collisions.

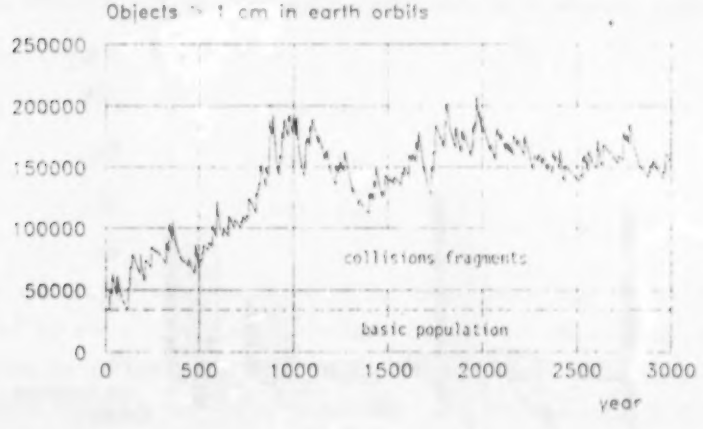

Fig. 11 Evolution of the population for a constant basic population as of 1989

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Future increase of the basic population

It has to be assumed that the basic population will increase further on, at least in the near-therm future. The results of some of these more realistic scenarios are shown in Fig. 12.

After a phase of a steady increase for 25 and 30 years, respectively, a constant basic population of the meanwhile reached level was assumed. A further steady increase of the basic population would lead always more or less fast to a chain reaction of collisions. The most probable increase rates for the near-therm future are about 1,750 objects per year (scenario 2, corresponding to the evolution during the last years) and 5 % per year (scenario 3, corresponding to NASA assumptions, see NASA-TM-100471). Therefore this critical basic population could be reached within only a few decades, if spaceflight activities will be continued as in the past.

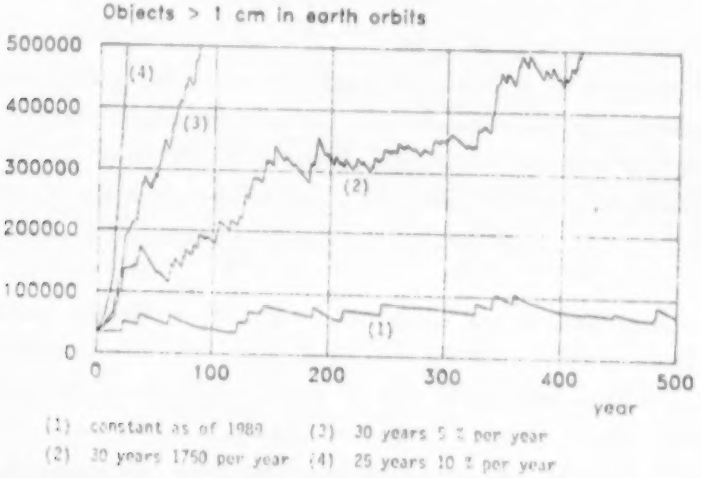

Fig. 12 Evolution of the population for different increase rates of the basic population

Importance of the larger objects

The collision risk will rise basically squared with the number of objects in earth orbits. But only the larger objects, as potential sources for the generation of a large number of fragments by collisions, are decisive for the setting-in of a chain reaction. To demonstrate the importance of the larger

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objects for the evolution of the population, a scenario without any small object within the basic population has been simulated. This extreme scenario would mean that there are no explosion fragments and mission related objects, neither in the past nor in the future.

As Fig. 13 shows, even for such a basic population of only about 9,000 medium and larger objects, a chain reaction of collisions will set in. The small objects missing within the basic population will be replaced very soon by collision fragments. Only a little delay concerning the increase of the population could be established. Therefore the avoidance of small objects, as helpful this would be to reduce the collision risk in the near future, will not prevent a chain reaction of collisions.

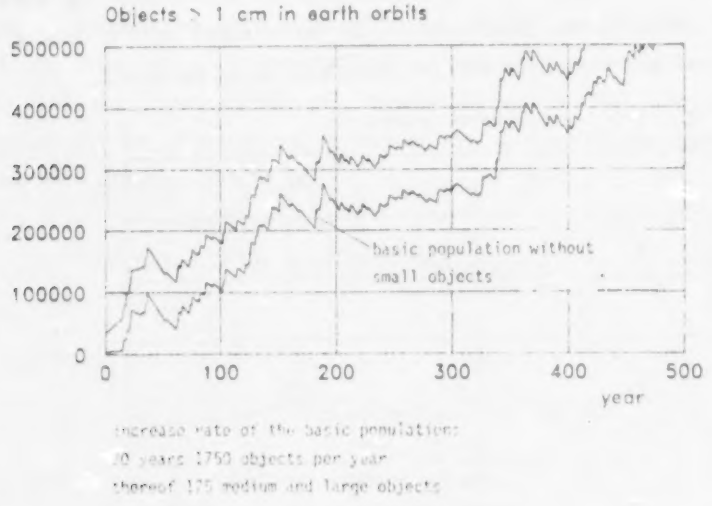

Fig. 13 Evolution fo the population for an assumed basic population without small objects

Summary

As a result of the detailed analysis, which was made possible by the use of a half-deterministic approach, it could be established that there is a risk of about 20 % per year for a collision among an assumed current population of about 35,000 objects larger than 1 cm in earth orbits. The risk for a cata-

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strophic collision, i. e. with the total destruction of the target and a significant generation of objects large enough to produce catastrophic collisions again, was found to be in the order of 3.7 % per year. Simulations of the evolution of the population assuming a constant basic population have shown, that the current population is not yet critical concerning a chain reaction of collisions. An equilibrium population including the collision fragments of about 150,000 - 200,000 objects larger than 1 cm could occur.

The collision risk will rise basically squared with the number of objects. But only the larger objects, as potential sources for the generation of a large number of fragments by collisions, are decisive for the setting-in of a chain reaction. Therefore the avoidance of smaller objects, such as explosion fragments or mission related objects, as helpful this would be to reduce the collision risk in the near future, will not prevent a chain reaction of collisions.

Besides the unknown evolution of the basic population, the greatest uncertainty concerning the chain reaction investigations is the poor knowledge of the two most important parameters, the number of generated collision fragments and their orbital lifetimes. Therefore, the results presented in this paper should not be taken as exact solutions, but only to describe the basic tendencies of the possible evolution of the population.

The critical population of larger objects for the setting-in of a chain reaction of collisions is only about 2 to 3 times the currentpopulation and could be reached within 20 to 50 years, if spaceflight activities will be continued as in the past. After exceeding this level a chain reaction could be prevented by reducing again the population to an uncritical level, but for hundreds of years then there would exist an unacceptable high population of collision fragments.

But even for a subcritical population the equilibrium fragment population in higher altitudes could be unacceptably high, endangering also the lower altitudes, e. g. for the International Space Station, due to the raining down effect.

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Conclusions and Recommendations

To prevent an unacceptable or critical high population in earth orbits, the number of larger objects should be limited to a level as low as possible. Therefore a new philosophy of spaceflight must be established: all objects brought into earth orbits have to be removed after the end of their missions, e. g. by an active controlled re-entry manoeuvre.

Indeed, for the next generation of the european launcher, ARIANE V, it is planned to remove the central stage from orbit shortly after the separation of the payload by a controlled braking thrust.

In addition, it could become necessary in the future to remove large object already in orbit, especially in the critical higher altitudes, to reduce an unacceptable or critical high population level.

A new strategy for the removal of a large number of large objects by controlled reentry is currently beeing investigated at the Institute of Space-flight Technology of the Technical University of Braunschweig.

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IV. ANALYSIS OF ORBITAL MANOEUVRES OF A LARGE SPACE STRUCTURE TO AVOID COLLISIONS WITH SPACE DEBRIS

Abstract

It is a well known fact that near earth space is crowded with man made objects, mainly pieces of space debris, causing a collision risk increasing with time. The use of large manned space structures (e. g. the International Space Station) in this space debris environment may eventually require a new kind of orbital manoeuvres, i. e. collision avoiding manoeuvres. Such manoeuvres may become necessary for larger debris particles, whereas the impact of particles up to 1 cm can be made ineffective by shielding.

The first step to reach a reliable impact avoiding method is the identification of those fragments that will have an encounter with the structure within a specific buffer zone. The range of that buffer zone and the time span remaining from identification until the encounter are important parameters.

Two methods of tracking fragments are conceivable. One is an onboard radar or optical system, another an earth based radar. The criteria for an effective use of these methods are the radar and optical cross sections of the fragments, detectability of fragments prior to their encounter due to visibility and their orbits.

The second step is, after the identification of a colliding object, the collision-avoiding manoeuvre itself, considering the precision of orbit predictions the propellant consumption, ug-level of the structure, and the possible combination of orbit keeping and avoiding manoeuvres.

Specific space debris scenarios can be used to assess the frequency of collision avoiding manoeuvres which may be necessary for future space structures.

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1. Introduction

Besides the active and spent satellites, there is a large numver of pieces of space debris orbiting the earth. Altogether, it is assumed that more than 60 000 objects larger than 1 cm are on low earth orbits between 200 and 2 500 km giving rise to a collision risk too high to be tolerated in manned missions. Only 10 % of these objects with a diameter of more than 10 cm can be tracked and catalogued at present.

The use of large manned space structures (e. g. the International Space Station) in this space debris environment will require eventually a new kind of orbital manoeuvres, i. e. collision avoiding manoeuvres. These manoeuvres will become necessary for larger space debris particles, where as the impact of particles up to 1 cm can be made ineffective by shielding.

Under the assumption of a 400 km operational orbit of the space structure, a certain fraction of the total object flux, which is in this altitude band, can lead to a collision. This part is reflected in the object density within a certain altitude range, measured in objects per km^3, and can also be described by the statistical object flux, which is the number of impacts per m^2 and year within this altitude range.

The current flux of objects > 1 cm at an altitude of 400 km is about 2×10^{-6} impacts per m^2 and year. This results in an overall collision risk of some percent for a space station of 1 000 m^2 surface within a 30 years mission. Due to the unknown future object flux this risk may increase. During space station in orbit operations there is a need for the deterministic prediction of possible individual collisions in order to enable subsequent countermeasures, such as avoiding manoeuvres. Other than shielding, active countermeasures cannot be based on statistical methods.

2. Survey on operational aspects of avoiding manoeuvres

There are a number of basic operational aspects of collision avoiding manoeuvres concerning the

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- detectability of all objects endangering the structure (risk objects)
- time span remaining from detection until impact (or close encounter)
- range of the buffer zone due to uncertainties during detection and determination of the orbits of the risk objects
- number of close encounters within this buffer zone and number of avoiding manoeuvres necessary.

These aspects determine the efficiency and frequency of avoiding manoeuvres. But there are also direct influences of such manoeuvres on the scheduled space station operations, e. g.

- fuel consumption
- µg-level of the structure
- operation costs.

All of these influences are direct proportional to the velocity increments and the thrust forces of the avoiding manoeuvres and to the frequency with which they may become necessary.

3. Analysis of an on-board detection system

The use of a detection system located on board a space structure requires that a risk object will be detectable a certain time prior to collision. This time must be long enough to enable an avoiding manoeuvre but on the other hand it must not be excessively long to limit prediction uncertainties. If the space structure and the risk object have similar orbital periods this requirement can be met.

The example in fig. 14 shows the orbit of the space structure and of a risk object and the positions (1-4) indicate the locations of the space structure one to four revolutions prior to collision at the time the fragment passes the station orbit. A computer simulated detection system installed to scan the xz-plane (horizontal plane of the station shown in Fig. 15) would see this risk object as infig. 16.

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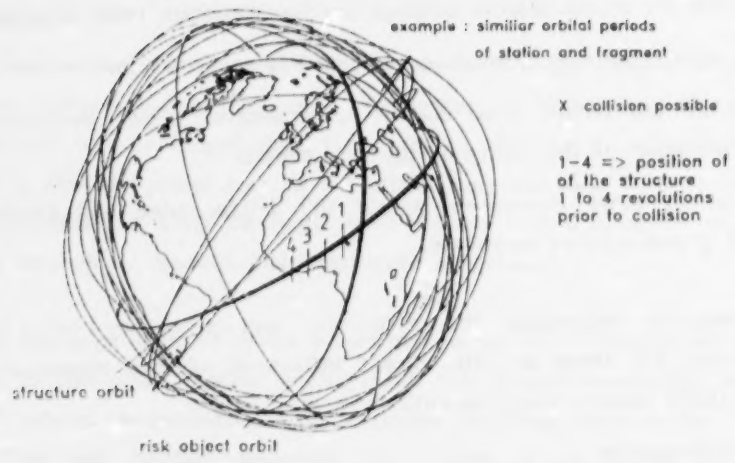

Fig. 14 The possibility of on-board detection

The following parameters describe the efficiency of this kind of detection sequence

t_d = detection period (i. e. the timespan during which a risk object is within the detection range r (s. Fig. 15)

n_d = number of detection periods prior to collision

t_f = absolute point in time of the final detection period prior to collision, on which the decision for an avoiding manoeuvre is based

These parameters strongly depend on the maximum range of the detection device and on the fragment orbital elements. For the following, an upper detection range limit of 500 km is assumed at this stage of the analysis.

The example given in fig. 16 yields 4 detection periods (n_d) of 1 to 2 minutes each (t_d) and a final detection during the last 10 hours (t_f) prior to collision. The long term history of the distance between the fragment and the station is given in fig. 17.

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But there are other objects that can not be detected by an on-board system within the last revolutions of the station prior to the collision because their orbital periods differ too much.

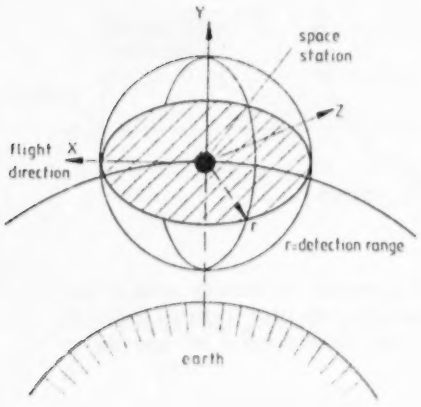

Fig. 15 The horizontal plane of an on-board detection system

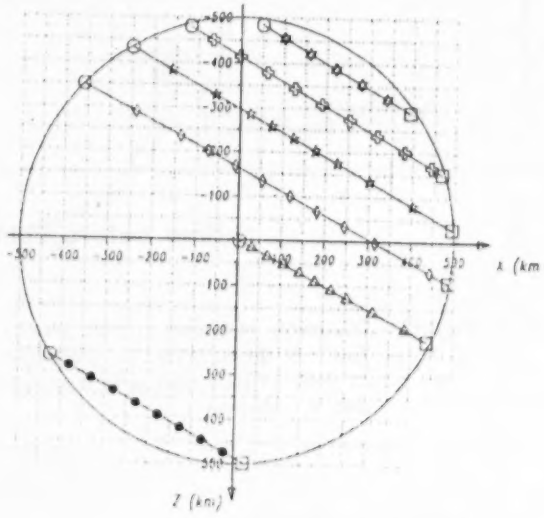

Fig. 16 The encounters of a risk object within a space structure's horizontal plane a few revolutions prior to collision (example: similar orbital periods of risk object and space structure)

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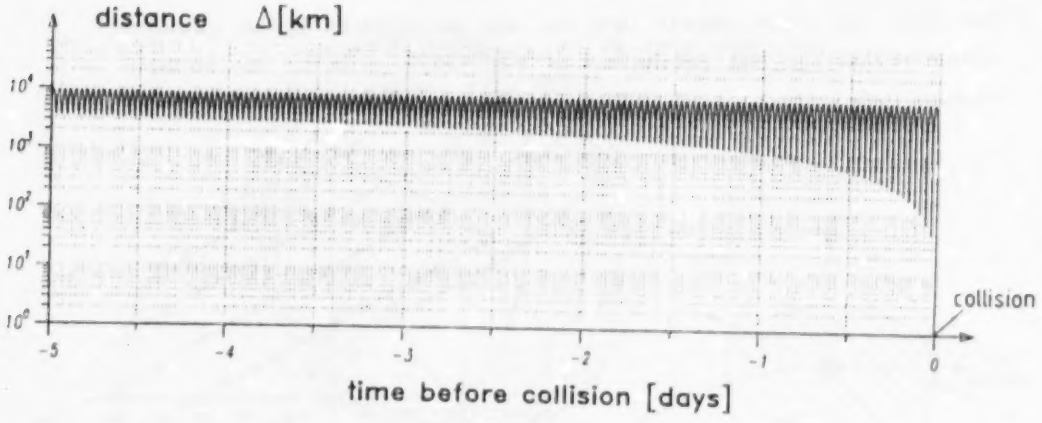

Fig. 17 Distance between a risk object and a space structure within the final 5 days prior to collision (example: similar orbital periods of risk object and space structure, one oscillation corr sponds to one revolution)

4. Possible Avoiding Manoeuvres

One possible avoiding manoeuvre consists of a tangential thrust puls which increases the semi major axis of the station orbit (s. fig. 18). The consequences of such a manoeuvre are

- an increase of the orbital period of the station resulting in a changed position as function of time
- a change of the eccentricity of the station orbit
- an increase of the station altitude profile.

The increase of the altitude profile can be seen as part of the scheduled operational altitude keeping strategy which is required anyhow to balance the drag. Additional fuel would not be necessary.

There is a semi major axis increase of about 900 m per 0.5 m/s velocity increment. The eccentricity of the orbit changes in an order of magnitude between 10^{-4} to 3×10^{-3} due to this kind of manoeuvre. The practical aspects with regard to space station operations are currently examined.

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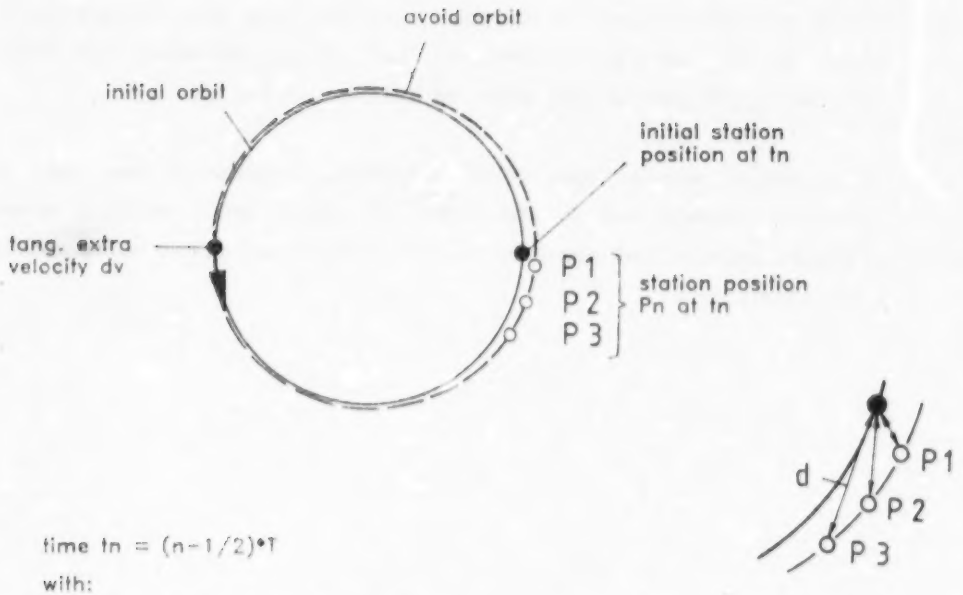

Fig. 18 A possible collision avoiding manoeuvre

5. Summary

A final assessment of the feasibility and efficiency of collision avoiding manoeuvres and of on-board detection of possible collision objects is not yet possible. More analysis is required and work on these subjects is going on.

But some preliminary conclusions can be drawn. A part of those objects which may lead to a collision within the next few hours or days can be detected by an on-board system. Such a time span prior to collision may enable reliable decisions on the necessity and the feasibility of an avoiding manoeuvre.

The avopiding manoeuvre itself (tangential thrust, raising the orbital altitude) can be performed with less than 1 m/s velocity increment. This

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causes a position change of the space structure depending on time which seems to be sufficient. Additional fuel is not required, for these manoeuvres are part of the scheduled altitude keeping strategy.

So it seems possible that collision avoiding manoeuvres can make a substantial contribution to the safety of future space stations, space transport systems and platforms in the present and future space debris environment.